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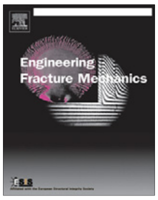

A study of the effect of the electro-mechanical loading history on the fracture strength of piezoelectric material

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ABSTRACT

Many studies to grasp and describe the fracture behavior of piezoelectric materials under electro-mechanical loading have been done. Although the crack energy density (CED) theory predicts that the mechanical and electrical CEDs can depend on the loading history, the effect of electro-mechanical loading history on the fracture strength of piezoelectric materials has not been studied. Therefore, in this paper, a fracture criterion based on the mechanical contribution of CED (CEDM) is introduced. Its applicability is studied by analyzing the results of three-point bending test regarding the loading path dependence of the fracture strength of piezoelectric ceramic. From the results of $(E \rightarrow M)$ and $(M \rightarrow E)$ tests for a C-21 piezoelectric ceramic specimen, it was found that the fracture behavior of piezoelectric ceramics depend on the loading history. The results further showed that the effect of the electric field on the fracture strength of piezoelectric ceramic in the $(M \rightarrow E)$ test was larger than that in the $(E \rightarrow M)$ test. Results from linear FE analyses, which assumed that the fracture-initiating load was the same, indicated that the CEDM values increased linearly from negative to positive, and the slopes of CEDM in descending order were: linear $(M \rightarrow E)$ analysis > linear (M, E) analysis > linear $(E \rightarrow M)$ analysis.

1. Introduction

In recent years, encouraging progress has been made in developing advanced materials with optical, mechanical and electromagnetic properties to meet the demanding engineering applications. A piezoelectric material is one such advanced material that has been widely used to generate an electrical charge from an applied mechanical force (direct piezoelectric effect) and a mechanical force from an applied electrical field (reverse piezoelectric effect). The properties of piezoelectric materials have made them especially attractive for use in sensors, actuators, etc.

In the past decades, Lead Zirconate Titanate (PZT) was the most commonly used piezoelectric material because of its superior properties compared to Barium Titanate. Several piezoelectric materials have since then been developed. However, for effective application of piezoelectric materials, it is important that their fracture behavior be known. Accordingly, a number of studies have been initiated to evaluate fracture strengths of piezoelectric materials. Most of the studies [1–5] have however, been based on the influence of electric field on the fracture behavior of piezoelectric materials. To explain the fracture responses of piezoelectric materials, a number of criteria have been proposed but none seems satisfactory. The stress intensity [6], the *J*-integral and energy release rate [7,8], the strain energy density vector [9,10], the local energy release rate [11], the mechanical strain energy release rate [2], etc., have been suggested as the traditional fracture criteria or fracture parameters. However, these criteria are applicable to specific conditions and do not fully explain the experimental results.

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Nomenclature

A	closed area surrounded by an arbitrary path surrounding the crack tip
c_{ij}^{E}	elastic stiffness constants measured at a constant electric field
D_i	electric displacement components
E_i	electric field components
e_{ij}	piezoelectric stress constants
ε_{ij}	strain components
f_i	body force components
G	energy release rate
n_i	outward unit normal vector
q_b	free charge density
q_s	surface charge density
S	arbitrary closed surface
T_i	traction vector components
u_i	components of displacement vector
V	volume of the region surrounded by S
W	extended strain energy density
W^M	mechanical contribution of extended strain energy density
W^E	electrical contribution of extended strain energy density
X_i	Cartesian coordinate axes
$\mathcal{E}$	crack energy density (CED)
$\mathcal{E}^M$	mechanical part of crack energy density (CEDM)
$\mathcal{E}^E$	electrical part of crack energy density (CEDE)
ϕ	electric potential
Γ	arbitrary path surrounding the crack tip
Γ_0	semicircular path along a notch-like crack tip
$\kappa_{ij}^{\varepsilon}$	dielectric permittivities under constant strain.
ρ	root radius of notch
σ_{ij}	stress components

Experimental work by Tobin and Pak [1] has played a significant role in understanding the fracture behavior of piezoectric materials. The authors used a Vickers indentation technique to investigate the fracture response of a PZT-8 ceramic and observed no change in crack length for cracks parallel to the poling direction. However, for cracks perpendicular to the poling direction, the crack lengths under positive electric fields were greater than those under negative electric fields.

By mechanically loading a compact tension (CT) specimen made of PZT-4 ceramic after application of an electric field (hereafter called the "($E \rightarrow M$) test"), Park and Sun [2] recorded similar results as those of Tobin and Pak. A finite element analysis by the authors where both mechanical and electrical loads were applied simultaneously (hereafter referred to as "(M, E) analysis"), showed that the mechanical strain energy release rate criterion can be used to predict the fracture loads with greater accuracy.

Although experimental results by Fang et al. [3] from ($E \rightarrow M$) test using the Center Crack Test on PZT-5 ceramic showed agreement with Tobin and Pak's findings, the numerical results from (M, E) analysis indicated that the total energy release rate was in total disagreement with the experimental data. However, the mechanical strain energy release rate and the local energy release rate agreed well with the experimental results.

From an ($E \rightarrow M$) test on a PZT-EC-65 ceramic using Vickers indentation technique, Wang and Singh [4] observed results different from those obtained by Tobin and Pak; the crack was shorter under negative electric fields than under positive electric fields for both cases poled in parallel and perpendicular to the crack surface. The authors also obtained radial, tangential and hoop stresses using (M, E) finite element analysis; but noted that only the hoop stress was important for crack propagation and that FEA results were consistent with the crack propagation behavior of PZT under electro-mechanical loadings.

Fu and Zhang [5] conducted ($E \rightarrow M$) tests on CT specimens and (M, E) finite element analysis, and observed that both positive and negative electric fields aid the fracture of the PZT-841 piezoelectric ceramic. They suggested that the energy release rate can be determined by the applied mechanical load and the geometry of specimen. The authors further noted that the critical stress intensity factor (fracture toughness) changed according to the applied electric field after confirming the energy release rate for a slit insulator crack is independent of the applied electric field.

It is observed that many experiments on the fracture behavior of piezoelectric materials exist; but these are primarily conducted by applying a mechanical load subsequent to an electric load, i.e. "($E \rightarrow M$) test". However, the ($M \rightarrow E$) test has never been experimentally attempted. In addition to "($E \rightarrow M$) test" experiments that have been widely studied, numerical work based on "(M, E) analysis" has been done.

As known above researches, many studies have suggested the mechanical contribution of the total stored energy as the fracture criterion of piezoelectric material. Nam and Watanabe [12–15] proposed the concept of crack energy density (CED)